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TITLE:

METHOD AND APPARATUS GENERATING AND DETECTING
TORSIONAL WAVE INSPECTION OF PIPES OR TUBES

INVENTORS:

Hegeon [NMI] Kwun
Sang-Young Kim
James F. Crane
Myoung-Seon Choi

# BACKGROUND OF THE INVENTION

This is a continuation in part patent application depending from U.S. Patent Application Serial No. 09/815,017, filed July 17, 2001, which is a continuation in part application depending from U.S. Patent Application Serial No. 09/519,530 filed February 25, 2000, now U.S. Patent No. 6,294,912, which depends on Provisional Patent Application Serial No. 60/124,763 filed March 17, 1999, now abandoned.

## 1.    FIELD OF THE INVENTION

The present invention relates generally to methods and devices for the nondestructive evaluation of materials. The present invention relates more specifically to a magnetostrictive sensor based system for the long range inspection of pipes and tubes made from ferromagnetic material.

## 2.    DESCRIPTION OF THE RELATED ART

Magnetostrictive effect refers to the phenomena of a physical dimension change in ferromagnetic materials that occurs through variations in magnetization. In magnetostrictive applications, the generation and detection of mechanical waves is typically achieved by introducing a pulse current into a transmitting coil adjacent to a ferromagnetic material. The change in magnetization within the material located near the transmitting coil causes the material to change its length locally in a direction parallel to the applied field. This abrupt local dimension change, which is the magnetostrictive effect, generates a mechanical wave (called guided wave) that travels through the ferromagnetic material with a certain fixed speed (which is usually less than the speed of sound). When the mechanical wave is reflected back from the end of the ferromagnetic material, or from a defect in the ferromagnetic material, and reaches a

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1 detection coil, the mechanical wave generates a changing magnetic flux in the detection coil as a

2 result of the inversed magnetostrictive effect. This changing magnetic flux induces an electric

3 voltage within the detection coil that is proportional to the magnitude of the mechanical wave.

4 The transmitting coil and the detection coil can be identical.

5 Advantages of using the magnetostrictive effect in nondestructive evaluation (NDE)

6 applications include (a) the sensitivity of the magnetostrictive sensors, (b) durability of the

7 magnetostrictive sensors, (c) no need to couple the sensor to the material being investigated,

8 (d) long range of the mechanical waves in the material under investigation, (e) ease of

9 implementation, and (f) low cost of implementation.

10 The use of magnetostrictive sensors (MsS) in the nondestructive evaluation (NDE) of

11 materials has proven to be very effective in characterizing defects, inclusions, and corrosion

12 within various types of ferromagnetic and non-ferromagnetic structures. A MsS launches a short

13 duration (or a pulse) of guided waves in the structure under investigation and detects guided

14 wave signals reflected from anomalies such as defects in the structure. Since guided waves can

15 propagate long distances (typically 100 feet or more), the MsS technique can inspect a global

16 area of a structure very quickly. In comparison, other conventional NDE techniques such as

17 ultrasonics and eddy current inspect only the local area immediately adjacent to the probes used.

18 Therefore, the use of magnetostrictive sensors offers a very cost effective means for inspecting

19 large areas of steel structures such as strands, cables, pipes, and tubes quickly with minimum

20 support requirements such as surface preparation, scaffolding, and insulation removal. The

21 ability to use magnetostrictive sensors with little preparation of the object under inspection

22 derives from the fact that direct physical contact between the sensors and the material is not

1   required.

2       Efforts have been made in the past to utilize magnetostrictive sensor technologies in

3   association with the inspection of both ferromagnetic and non-ferromagnetic materials. Included

4   in these efforts are systems described in U.S. Patent Nos. 5,456,113; 5,457,994; and 5,501,037,

5   which are each commonly owned by the assignee of the present invention. The disclosures of

6   U.S. Patent Nos. 5,456,113; 5,457,994; and 5,501,037, provide background on the

7   magnetostrictive effect and its use in NDE and are therefore incorporated herein by reference.

8   These efforts in the past have focused primarily on the inspection of pipe, tubing and steel

9   strands/cables wherein the geometry of the structure is such that the cross-sectional diameter is

10  small in comparison to the length of the structure. While these systems and their application to

11  longitudinal structures find significant applications, there are yet other structures that could

12  benefit from the use of magnetostrictive based NDE.

13      Other efforts have been made in the past to utilize sensors that measure magnetic flux

14  and/or acoustic waves in structural materials. These efforts have included those described in the

15  following patents:

16      U.S. Patent No. 3,555,887 issued to Wood on January 19, 1971 entitled Apparatus for

17  Electroacoustically Inspecting Tubular Members for Anomalies Using the Magnetostrictive

18  Effect and for Measuring Wall Thickness. This patent describes a system designed to direct a

19  mechanical wave through the thickness dimension of a long tubular member. The sensitivity of

20  the device is limited to the directing of a wavefront normal to the surface of the material under

21  inspection and immediately back to a sensor when reflected from an opposite wall or an anomaly.

22  U.S. Patent No. 4,881,031 issued to Pfisterer, et al. on November 14, 1989 entitled Eddy Current

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1    Method and Apparatus for Determining Structure Defects in a Metal Object Without

2    Removing Surface Films or Coatings. This patent describes a method for establishing localized

3    eddy currents within ferromagnetic materials and recognizes the presence and effect of a coating

4    in order to identify and quantify corrosion beneath the coating. As with other eddy current

5    methods, the ability to inspect a material is limited to the area immediately adjacent to the sensor.

6    U.S. Patent No. 5,544,207 issued to Ara, et al. on August 6, 1996 entitled Apparatus for

7    Measuring the Thickness of the Overlay Clad in a Pressure Vessel of a Nuclear Reactor. This

8    patent describes a system directed solely to the measurement of magnetic field variations that

9    result from the distribution of the magnetic field through overlays of varying thickness. The

10   system utilizes a magnetic yoke that is placed in close contact with the surface of the overlay clad

11   of the pressure vessel.

12        U.S. Patent No. 5,687,204 issued to Ara, et al. on November 11, 1997 entitled Method of

13   and Apparatus for Checking the Degradation of a Pressure Vessel of a Nuclear Reactor. This

14   patent describes a system similar to the earlier issued Ara, et al. patent and utilizes a magnetic

15   yoke having an excitation coil and a magnetic flux measuring coil that are placed in close contact

16   with the inner wall of the pressure vessel. The hysteresis magnetization characteristics formed by

17   the magnetic yoke and the pressure vessel wall are measured. Degradation of the material

18   comprising the pressure vessel is inferred from a determination of the hardness of the material

19   which is determined from the coercive forces obtained by analyzing the hysteresis characteristics

20   of the magnetization.

21        In general, a magnetostrictive sensor consists of a conductive coil and a means for

22   providing a DC bias magnetic field in the structure under inspection. The means for providing a

1    bias magnetic field can include the use of either permanent magnets or electromagnets. In a

2    transmitting magnetostrictive sensor, an AC electric current pulse is applied to the coil. The

3    resulting AC magnetic field (a changing magnetic field) produces guided waves in an adjacent

4    ferromagnetic material through the magnetostrictive effect. For pipes, cables, tubes, and the like,

5    the waves are typically launched along the length of the longitudinal structure. In the receiving

6    magnetostrictive sensor, a responsive electric voltage signal is produced in the conductive coil

7    when the guided waves (transmitted or reflected from anomalies within the material) pass the

8    sensor location, through the inverse magnetostrictive effect.

9            With MsS techniques, defects are typically detected by using the pulse-echo method well

10   known in the field of ultrasonics. Since the sensor relies on the magnetostrictive behavior found

11   in ferrogmagnetic materials, this technology is primarily applicable to the inspection of

12   ferromagnetic components such as carbon steel piping or steel strands. It is also applicable,

13   however, to the inspection of nonferrous components if a thin layer of ferromagnetic material,

14   such as nickel, is plated or coupled onto the component in the area adjacent to the

15   magnetostrictive sensors.

16           The magnetostrictive sensor technique has the advantage of being able to inspect a large

17   area of material from a single sensor location. Such sensors have, for example, been used to

18   accurately inspect a length of pipe or cable of significantly more than 100 feet. Further,

19   magnetostrictive sensor techniques are comprehensive in their inspection in that the methods can

20   detect both internal and external defects, thereby providing a 100% volumetric inspection. The

21   techniques are also quite sensitive, being capable of detecting a defect with a cross-section less

22   than 1% of the total metallic cross-section of cylindrical structures such as pipes, tubes, or rods.

1 | Finally, as indicated above, magnetostrictive sensor techniques do not require direct physical

2 | contact between the component surface and the sensor itself. This eliminates the need for surface

3 | preparation or the use of a couplant.

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5 | ## APPLICATION TO PLATE TYPE AND CONTAINMENT STRUCTURES

6 | In recent years, there have been many reported occurrences of steel containment liners

7 | degrading at commercial nuclear power plants. Due to the aging of such facilities and the

8 | increased requirements for inspection, incidents of degradation are likely to increase. The

9 | structural degradation of these liners, especially corrosion damage, is an important concern since

10 | the liners are designed to provide a leak-tight pressure boundary for the nuclear containment.

11 | Many other industrial uses of plate type ferromagnetic materials could benefit from more

12 | frequent inspections to determine the state of deterioration, the location of faults, and the

13 | likelihood of failure. In most instances in the past, inspections of large plate type objects (such

14 | as large aboveground storage tanks) have required either very expensive off-line inspections or

15 | statistical samplings of randomly selected local areas that are for the most part less than reliable.

16 | It has heretofore been difficult to carry out a thorough inspection of a plate type structure,

17 | or a structure comprised of a plurality of plate type sheets of material, without high cost and long

18 | down time for the object under inspection. It would be desirable to use the magnetostrictive

19 | sensor technique for detecting and locating various anomaly characteristics within plate type

20 | materials. Such techniques could be used for detecting and locating wall thickness reductions in

21 | liners, such as those described above, that might be caused by corrosion over time. If such a

22 | system were applicable, it would be possible to inspect otherwise inaccessible regions of

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1  containment liners and the like that are either imbedded in concrete or adjacent to flooring or

2  equipment that cannot be moved.

3  It would therefore be desirable to implement magnetostrictive sensor techniques in

4  conjunction with plate type structures in a manner similar to, and with the accuracy of, such

5  systems utilized in conjunction with cylindrical structures. It would be desirable if an inspection

6  of plate type and cylindrical structures could be carried out in an efficient manner that did not

7  require full access to the surface of the plate or the inner or outer surface of cylindrical structures

8  such as pipes and tubes. Such a magnetostrictive sensor system would be able to investigate

9  large volumes of a plate type or cylindrical structure, including pipes and tubes, and would

10  provide a cost effective global inspection of the structure.

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12  **SUMMARY OF THE PRESENT INVENTION**

13  It is therefore an object of the present invention to provide a sensor device for

14  implementing magnetostrictive based NDE in association with pipes and tubes in order to

15  evaluate the condition of the structures and to determine the presence of anomalies indicative of

16  fractures, deteriorations, and the like.

17  It is a further object of the present invention to provide a magnetostrictive sensor

18  appropriate for use in conjunction with the inspection of pipes and tubes that is capable of

19  transmitting and receiving guided waves within the pipes and tubes and generating signals

20  representative of the characteristics of such waves appropriate for the analysis and detection of

21  anomalies therein.

22  It is a further object of the present invention to provide magnetostrictive sensor devices

1  appropriate for use in conjunction with the inspection of pipes and tubes that inspect the entire

2  structure for anomalies, corrosion, fractures, and the like in a cost effective manner.

3      It is a further object of the present invention to provide a method for the inspection of

4  pipes and tubes that includes the use of a magnetostrictive sensor specifically adapted for

5  directing guided waves along the length of the pipe or tube and detecting such waves as may be

6  reflected from anomalies along the pipe or tube.

7      It is yet another object of the present invention to provide a method and apparatus for

8  nondestructive evaluation of pipes and tubes utilizing magnetostrictive sensors that generate and

9  detect shear horizontal waves along the length of the item being inspected.

10     It is yet another object of the present invention to provide a magnetostrictive sensor that is

11  suitable for low frequency operation (200 kHz or less), has good sensitivity and long inspection

12  range, and is relatively tolerate to liftoff.

13     It is still another object of the present invention to provide a method and apparatus for

14  nondestructive evaluation of pipes using magnetostrictive sensors that propagate guided waves in

15  a circumferential direction around the pipe.

16     Another object of the present invention is to provide a method and apparatus for

17  nondestructive evaluation of pipes and tubes using magnetostrictive sensors with

18  torsional waves that has better defect detectability particularly in liquid filled pipes or

19  tubes.

20     In fulfillment of these and other objectives, the present invention provides an

21  improved method and apparatus for implementing magnetostrictive sensor techniques for

22  the nondestructive evaluation of plate type structures such as walls, vessels, enclosures,

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1 and the like. The system includes magnetostrictive sensors specifically designed for

2 application in conjunction with welded plate type structures that generate guided waves in

3 the plates which travel through the plate in a direction parallel to the surface of the plate.

4 Similarly structured sensors are positioned to detect the guided waves (both incident and

5 reflected) and generate signals representative of the characteristics of the guided waves

6 detected. The system anticipates the use of either discrete magnetostrictive transmitters

7 and receivers or the use of a single magnetostrictive sensor that operates to both transmit

8 and detect the guided waves. The sensor structure is longitudinal in nature and generates

9 a guided wave having a wavefront parallel to the longitudinal direction of the sensor.

10 Appropriate electronics associated with the process of generating the guided waves and

11 controlling the propagation direction of the generated wave through the magnetostrictive

12 transmitter as well as detecting, filtering, and amplifying the guided waves at the

13 magnetostrictive receiver, are implemented as is well known in the art. Signal analysis

14 techniques, also known in the art, are utilized to identify anomalies within the plate type

15 structure. The method utilizes pattern recognition techniques as well as comparisons

16 between signal signatures gathered over time from the installation of the structure under

17 investigation to a later point after deterioration and degradation may have occurred.

18     The magnetostrictive sensors can also be used to detect defects in cylindrical structures

19 such as to detect defects in electric resistance welding, such as in pipes that are welded along a

20 seam thereof. For example, a magnetostrictive transmitter can be placed on one side of the pipe

21 being investigated and a magnetostrictive receiver on the other side of the pipe. By propagating a

22 guided wave in circumferential direction around the pipe, any defects in the pipe can immediately

1  be detected, such as in the area of the weld.  For generation and detection of the symmetrical (S)

2  or the anti-symmetrical (A) Lamb wave mode in a plate type structure, the DC magnet or field

3  required for MsS operation is applied parallel to the direction of wave propagation.  For

4  generation and detection of the shear horizontal (SH) wave mode, the DC magnetic field required

5  for MsS operation is applied perpendicular to the direction of wave propagation.  Due to the

6  enclosed nature of cylindrical structures such as pipes and tubes, the shear horizontal wave can

7  be induced to act as a torsional wave along the length of the pipe or tube. The generation of a

8  shear horizontal or torsional wave along the length of the pipe or tube allows defect detectability

9  that will not be hampered by the presence of liquid in the pipe or tube.

10  Current flow along the longitudinal axis of a pipe or tube will cause magnetization of a

11  ferromagnetic pipe or tube in the circumferential direction.  This magnetization can be used for

12  the transmission and detection of torsional waves that flow along the pipe and tube and any

13  reflections thereof.  The reflections may be from anomalies or defects in the pipe or tube.

14  Also, a thin ferromagnetic strip that is magnetized in the circumferential direction may be

15  wrapped around and held tightly against the pipe or tube.  Thereafter, a torsional wave may be

16  generated or detected where the ferromagnetic strips are located along the pipe or tube.  The

17  circumferential magnetization around the pipe or tube is in the ferromagnetic strip.  It is very

18  important to hold the ferromagnetic strip in tight surface contact with the pipe or tube so that the

19  full effect of the torsional wave can be felt and detected in either the transmitter or receiver coils

20  adjacent thereto.

21  The material used for the thin ferromagnetic strip has a high magnetostrictive coefficient,

22  is operable with residual magnetization and is able to withstand the applied AC magnetic fields,

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1   has a high mechanical strength, has a high Curie temperature, and has to be available in strip

2   form. Nickel has been used in the present invention with success. However, for improved

3   efficiency, the thin ferromagnetic strip is composed of an iron-cobalt alloy. It is preferred that

4   the iron-cobalt alloy be composed of at least 40% by weight iron metal and at least 40% by

5   weight cobalt metal. Most preferably, the preferred iron-cobalt alloy consists of 48.94% iron,

6   48.75% cobalt, 1.90% vanadium, 0.30% niobium, 0.05% manganese, 0.05% silicon, and 0.01%

7   carbon.

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9                     **BRIEF DESCRIPTION OF THE DRAWINGS**

10       FIG. 1 is a schematic block diagram showing the components of the system of the present

11   invention.

12       FIG. 2 is a perspective view of a magnetostrictive sensor of the present invention.

13       FIG. 3 is a cross-sectional view of the implementation of the sensors of the present

14   invention in conjunction with a plate type structure.

15       FIG. 4 is a plot of a signal received through the system of the present invention utilizing a

16   60 kHz symmetric ($S_0$) wave mode signal in a 4 foot wide, 20 foot long, 0.25 inch thick steel

17   plate.

18       FIG. 5 is a plot of a signal received through the system of the present invention in

19   conjunction with the structure associated with FIG. 4 for a 40 kHz anti-symmetric ($A_0$) wave

20   mode signal.

21       FIG. 6 is a plot of three signals received through the system of the present invention

22   utilizing a 40 kHz symmetric ($S_0$) wave mode signal in a 4 foot wide, 20 foot long, .25 inch thick

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steel plate.

FIG. 7 is a plot of three signals received through the system of the present invention utilizing a 20 kHz anti-symmetric ($A_0$) wave mode signal in a 4 foot wide, 20 foot long, .25 inch thick steel plate.

FIGS. 8(a) and (b) are plots of a shear horizontal (SH) wave received through the system of the present invention utilizing an 80 kHz wave in a 4 foot wide, 20 foot long .25 inch thick steel plate, before and after a .05 inch hole is cut therein.

FIG. 9 is a pictorial end view of a welded pipe being inspected using a magnetostrictive transmitting probe and a magnetostrictive receiving probe on opposite sides of the pipe for transmission and receipt of Lamb or SH waves.

FIGS. 10(a) and (b) are plots of signals received through the system of the present invention when used to test a pipe as shown in Fig. 9, utilizing a 150 kHz SH wave mode in a 4.5 inch outside diameter steel pipe having a .337 inch thick wall before and after cutting a notch therein.

FIG. 11 is a pictorial view of a pipe being inspected using a magnetostrictive transmitting probe and a magnetostrictive receiving probe for transmission and receipt of torsional waves with a high DC electric current for circumferential magnetization.

FIG 12 are plots of torsional wave signals received through the system of the present invention depicted in Fig. 11 when used to test a pipe filled with water, utilizing a 32 kHz torsional wave mode in a 4.5 inch outside diameter steel pipe having a 0.337 inch thick wall and 168 foot length.

FIG. 13 is an illustration of different types of magnetostrictive waves in a plate to

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1 | illustrate dimensional changes in the plate.

2 | FIG. 14 is a cross-sectional view of a transmitter or receiver attached to a pipe for

3 | transmission or receipt of torsional waves.

4 | FIG. 15 is another embodiment of a cross-sectional view of a transmitter or receiver

5 | attached to a pipe for transmission or receipt of torsional waves.

6 | FIG. 16 is a plot of a signal received using the embodiment as shown in Fig. 14 on a 9.3

7 | foot long pipe having 4 inch outside diameter and a .224 inch thick wall, with the transmitters

8 | and receivers being located on each end of the pipe.

9 | FIG. 17 is yet another embodiment of a cross-sectional view of a transmitter and receiver

10 | attached to a tube for transmission or receipt of torsional waves from inside the tube.

11 | FIG. 18 is a plot of the MsS signals obtained with HYPERCO-50HS and Nickel at an

12 | MsS operating frequency of 128 kHz.

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14 | ## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

15 | As indicated above, the present invention utilizes the basic methodological approach of

16 | earlier developed magnetostrictive sensor techniques associated with the inspection of cylindrical

17 | structures such as pipe, tubes, and the like. The basic system of such techniques is combined

18 | with a novel magnetostrictive sensor for application to plate type structures. Reference is made

19 | first to FIG. 1 for a general description of the complete system utilized to carry on the inspection

20 | of a plate type structure. Inspection system 10 includes a magnetostrictive sensor transmitter

21 | control 12 and an associated transmitter coil/core 14. Transmitter coil/core 14 is positioned

22 | adjacent to the surface of plate type structure 34. Also positioned near the surface of plate type

1    structure 34 is receiver coil/core 20. Receiver coil/core 20 is positioned to detect reflected waves

2    within plate type structure 34 and to thereby generate a signal representative of the wave

3    characteristics that are reflected from a defect present in the structure. Receiver coil/core 20 is

4    connected to preamp/filter 18 which in turn is connected to computer system 16.

5         Magnetostrictive sensor transmitter control 12 is comprised of function generator 22,

6    power amplifier 24, and synchronization circuitry 26. These elements together generate an

7    appropriate signal for driving transmitter coil/core 14 and thereby generate guided waves within

8    plate type structure 34.

9         Computer system 16 is comprised of memory 28, digital processor 30, and analog to

10    digital converter 32. These components together receive, digitize, and analyze the signal

11    received from receiver coil/core 20. The signal contains wave characteristics indicative of the

12    characteristics of the reflected guided waves present in plate type structure 34.

13         Both transmitter coil/core 14 and receiver coil/core 20 have associated with them bias

14    magnets 36 and 38, respectively. Bias magnets 36 and 38 are positioned adjacent the coils/cores

15    14 and 20 near plate type structure 34 in order to establish a bias magnetic field to facilitate both

16    the generation of guided waves within structure 34 and the appropriate detection of reflected

17    guided waves.

18         Reference is now made to FIG. 2 for a detailed description of the novel magnetostrictive

19    sensor structure utilized in the present invention. Magnetostrictive sensor 11 as shown in FIG. 2

20    could be utilized as either transmitter coil/core 14 or receiver coil/core 20 described above in

21    FIG. 1. Magnetostrictive sensor 11 is comprised of a plurality of U-shaped cross-sectional cores

22    stacked in a lengthwise direction to form a sensor with a longitudinal axis that is long in

1   comparison to its cross-section. Core elements 15a through 15n in the preferred embodiment

2   may be made from a stack of U-shaped ferrites, transformer steel sheets, mild steel, or permanent

3   magnets. The core elements 18a through 15n could have other shapes; however, U-shaped or

4   E-shaped core elements have been found to be more efficient. If an E-shaped core is used, a

5   transmitter may be located on one part of the E with a receiver on the other part of the E.

6   Surrounding the stack of U-shaped cores 15a through 15n is wire coil 17. The number of turns

7   for coil 17 is dependent upon the driving current and the magnetic permeability of core 15 and

8   may be varied as is well known in the art.

9         FIG. 3 shows in cross-sectional view the application of a pair of sensors structured as

10   shown in FIG. 2 and implemented in conjunction with the methods of the present invention. In

11   FIG. 3, a cross-section of plate type structure 34 is shown with transmitter coil/core 14 and

12   receiver coil/core 20 positioned on the plate. The view in FIG. 3 of both transmitter coil/core 14

13   and receiver coil/core 20 is cross-sectional in nature in order to show the establishment of a

14   magnetic flux within plate type structure 34. Associated with each of the coils/cores 14 and 20

15   are bias magnets 36 and 38. In FIG. 3, bias magnets 36 and 38 are shown placed over coils/cores

16   14 and 20. It is understood that in the actual implementation of the present invention, bias

17   magnets 36 and 38 may be one or two magnets. What is necessary is that a magnetic field be

18   generated in plate type structure 34 under the transmitter coil/core 14 and the receiver coil/core

19   20. It is only critical that the DC bias magnetic fields established by bias magnets 36 and 38 are

20   established within the volume of plate type structure 34 under transmitter coil/core 14 and under

21   receiver coil/core 20 as appropriate.

22         Transmitter coil/core 14 is comprised of core material 40 and coil windings 42. Together

1  these components, as driven by the magnetostrictive sensor transmitter control (not shown),

2  operate to generate changes in the magnetic field established by bias magnet 36 within plate type

3  structure 34. This time-varying or AC magnetic field within plate type structure 34 generates a

4  guided wave that propagates in a direction parallel to the surface of plate type structure 34. This

5  guided wave is depicted as wave 50 in FIG. 3 and propagates in a direction away from

6  transmitter coil/core 14. If, as shown in FIG. 3, transmitter coil/core 14 is placed on the surface

7  of plate type structure 34, with the longitudinal axis of coil/core 14 directed into the drawing

8  page in the view shown, wave 50 would propagate in two directions away from the longitudinal

9  axis of coil/core 14 and through plate type structure 34. This would serve to investigate the

10  volume of plate type structure 34 bounded by the length (long axis) of the magnetostrictive

11  sensor utilized. In this manner, an inspection "sweep" of a volume of plate type structure 34 can

12  be carried out generally equal in width to the length of the magnetostrictive sensor.

13      The arrangement of the magnetostrictive sensor utilized as the detection coil in the

14  present invention is essentially the same as the arrangement for the transmitter coil. In FIG. 3,

15  receiver coil/core 20 is comprised of core material 44, shown in cross-section, as well as coil

16  windings 46. Bias magnet 38 is likewise positioned over receiver coil/core 20. This arrangement

17  establishes a bias magnetic field within plate type structure 34 that fluctuates according to the

18  presence of reflected guided waves within the material adjacent the sensor. In FIG. 3, reflected

19  guided waves are depicted as 52 proximate to receiver coil/core 20 and are detected thereby. In

20  this manner, guided waves passing through plate type structure 34 under receiver coil/core 20 are

21  detected and "translated" into voltage fluctuations in coil 46 in a manner that generates an

22  appropriate signal for analysis by the balance of the electronics of the system of the present

1 invention (not shown).

2     As indicated above, the methods and apparatus of the present invention can be utilized in

3 conjunction with discrete magnetostrictive transmitters and receivers or in conjunction with a

4 single magnetostrictive sensor operable as both a transmitter and a receiver. In the latter case, the

5 structures described in FIG. 3 would be limited to a single magnetostrictive sensor of the

6 configuration shown for either transmitter coil/core 14 or receiver coil/core 20.

7     In another alternative approach, one with greater practical application, two transmitter

8 sensors and two receiver sensors may be used when the sensors are controlled by appropriate

9 phasing. In this manner, the direction of the interrogating beam may be controlled. As an

10 example, when the transmitter generates the wave in a first position (+) direction, the return

11 signals may be detected by a receiver controlled to detect waves traveling in the negative (-)

12 direction. As mentioned above, this control is achieved by phasing the two sensors

13 appropriately, a process well known in the field of NDE techniques. In this manner, an

14 inspection of the plate may be carried out first to one side of the transmitting sensor and then by

15 simply switching the sensor instrumentation an inspection may be carried out to the opposite side

16 of the transmitting sensor. Various other inspection techniques known and used with

17 magnetostrictive sensors may likewise apply with the methods and structures of the present

18 invention.

19     Reference is now made to FIGS. 4 and 5 for a detailed description of sample data

20 acquired from a 0.25 inch thick, 20 foot long, and 4 foot wide steel plate investigated by the

21 devices and methods of the present invention.

22     The signal represented in FIG. 4 shows the first symmetric wave mode ($S_0$) in the plate

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1 while the signal depicted in FIG. 5 shows the first anti-symmetric wave mode ($A_0$). FIG. 4 is a

2 time varying amplitude plot of a 60 kHz magnetostrictive sensor signal taken from the above

3 described steel plate geometry. The wave is directed through appropriate orientation of the

4 sensor and propagates in the long direction within the steel plate. The signal components

5 identified in FIG. 4 include the initial pulse 60, end reflected signal 62, and trailing signals 64.

6 Likewise in FIG. 5, initial pulse 70 is indicated, as are end reflected signals 72.

7 Anomalies within the path of the guided wave generated within the material would, as is

8 known in the art, generate signal components having amplitudes sufficient for identification

9 within either of the two signals shown in FIGS. 4 and 5. In this manner, characteristics of

10 anomalies detected within the plate type structure can be identified and located in the direction of

11 wave propagation away from the magnetostrictive sensor. As is known in the art, the relative

12 location of an anomaly may be identified by the position of the signal characteristic indicative of

13 the anomaly in time relationship with the initial pulse (indicative of the position of the sensor)

14 and the end reflected signals 62 and 72.

15 Examples of such signals are shown in FIGS. 6 and 7. FIG. 6 shows pulse-echo

16 magnetostrictive sensor data for a 40 kHz $S_0$ wave mode signal obtained in a 4 foot wide, 20 foot

17 long, .25 inch thick steel plate. Three signals are shown for data collected with a 4 inch long, 8

18 inch long, and 12 inch long notch cut in the plate at a point approximately two-thirds of the

19 length of the plate away from the sensor.

20 FIG. 7 shows pulse-echo magnetostrictive sensor data for a 20 kHz $A_0$ wave mode signal

21 obtained in a 4 foot wide, 20 foot long, .25 inch thick steel plate. Three signals are also shown

22 for data collected with a 4 inch long, 8 inch long, and 12 inch long notch cut in the plate at a

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1  point approximately two-thirds of the length of the plate away from the sensor.

2      In each case, the notch is not only detectable but may be characterized as to size and

3  position. Various signal analysis techniques may be applied to these signals to discern and

4  characterize other types of anomalies found in such plate-type structures. Discrete fractures and

5  the like are typically identified by isolated reflected waves, while broad deteriorations or

6  corrosions in the plate might be identified by grouped waves received over a period of time. In

7  addition, it is anticipated that signature signals of a particular plate type structure might be

8  acquired prior to implementation of the structure into service. In this manner subsequent

9  signatures may be acquired periodically and compared with the initial base line reference

10  signature to determine the presence of developing anomalies within the plate.

11      To prove the invention works, symmetric ($S_0$) and anti-symmetric ($A_0$) longitudinal wave

12  mode signals were generated and detected using a 12 inch long magnetostrictive probe such as

13  shown in Fig. 2. To generate and detect these wave modes, the bias magnets 36 and 38 are

14  applied in the direction parallel to the direction of wave propagation (perpendicular to the

15  lengthwise length of the magnetostrictive probe). The same probe as shown in Fig. 2 can be used

16  to generate and detect shear horizontal waves in a plate by applying DC bias magnetic fields in a

17  direction perpendicular to the wave of propagation (or parallel to the lengthwise direction of the

18  magnetostrictive probe).

19      Using a 4 inch long magnetostrictive probe, a signal was induced in a .25 inch thick,

20  4 foot wide, 20 feet long, steel plate. Fig. 8(a) shows the signal as generated and reflected over

21  time. The initial pulse 100 is generated by the magnetostrictive transmitter controller 12 until it

22  reaches the far end of the sheet and a signal from the far end 102 is received by the receiver

20

1  coil/core 20. A signal from the near end 104 is received due to the imperfect directionality

2  control of the system.

3      After drilling a .25 inch hole about two-thirds of the way down the sheet, another initial

4  pulse 100 is sent down the sheet. Again, a signal is received from the near end 104 due to

5  imperfect directionality control. Also, a signal 102 from the far end is received. However, now a

6  signal 106 is received that indicates the .25 inch hole in the sheet. Therefore, Figs. 8(a) and (b)

7  in combination clearly illustrate that shear horizontal waves can be used in the magnetostrictive

8  inspection techniques and probes of the current invention. Also, the magnetostrictive testing of

9  the large plate structures is suitable for low frequency operation (200 kHz or less), has good

10 sensitivity and long range inspection, and is relatively tolerate to liftoff. This is not the case if

11 the inspection technique had used other common nondestructive evaluation techniques, such as

12 electromagnetic acoustic transducers.

13      Pipes can be considered as plates that are simply bent in a circle. Pipes are literally made

14 from sheet metal that is bent into a circle and welded on one side thereof utilizing electric

15 resistance welding. Magnetostrictive inspection techniques may be used to inspect such pipes as

16 shown and explained in connection with Fig. 9, including the electric resistance welding. A pipe

17 200 is shown with a weld line 202. A transmitter coil/core 14 is located on one side of the pipe

18 200 and a receiver coil/core 20 is located 180° on the opposite side of the large diameter pipe

19 200. While not shown, magnetic bias is provided adjacent to the transmitter coil/core 14 and the

20 receiver coil/core 20. Using the inspection system 10 as shown in Fig. 1, an initial pulse 206 is

21 started around the pipe as shown in Fig. 10(a). Each time the pulse passes the receiver coil/core

22 20, a signal 208 is received. The signal 208 dies out over a period of time and after repeated

21

1  revolutions around the pipe 200.

2      If the transmitter coil/core 14 is 180° around the pipe 200 from the receiver coil/core 20,

3  the two opposite going waves add constructively producing a single large amplitude signal. Once

4  generated, the initial pulse 206 keeps revolving around the circumference of the pipe 200 until all

5  of its energy is dissipated. Therefore, the generated wave produces signals at regular intervals

6  which are equal to the transient time of the shear horizontal wave to travel around the full

7  circumference of the pipe 200. If there are any defects at the weld line 202, they will clearly be

8  indicated as defect signals. If the weld line is approximately 90° from transmitter coil/core 14,

9  then the defect would be approximately midway between the signals 208 as received by the

10  receiver coil/core 20.

11      To prove the measuring of the defects, the applicant, after measuring the signal as shown

12  in Fig. 10(a), cut a notch in the pipe 200. The test was then repeated with an initial pulse 206

13  inducing a shear horizontal wave around the circumference of the pipe 200. Again, signals 208

14  indicate each time the shear horizontal wave reaches the receiver coil/core 20. However, in

15  addition, there are notch signals 210 that are created by a reflected signal from the notch that has

16  been induced in the pipe 200. The notch signal 210 increases in amplitude with time because

17  each time the initial wave revolves around the pipe 200, it passes the notch defect thereby

18  producing a notch defect signal 210 which is then added to the previous notch defect signal 210.

19  The increasing of the notch signal 210 occurs for a period of time and then it will decrease until

20  its energy is dissipated, the same as signal 208.

21      It is possible to get a comparative indication as to the size of the defect by the ratio

22  between the first initial wave signal amplitude 208 and the first defect signal amplitude 210. In

22

1    the example illustrated in Fig. 10(b), the notch is approximately 8% of the cross-sectional area.

2    This compares well to the ratio of signal 208 to 210 being approximately 10%. This is intended

3    to be a rough generalization as to the size of the notch. Obviously, other factors would be

4    considered, such as whether the notch is perpendicular or parallel to the direction of travel of the

5    shear horizontal wave.

6          By use of the method as just described, the present invention can be used to inspect pipes

7    for longitudinal defects and corrosion defects. In the present method, the magnetostrictive

8    probes are moved along the length of pipe to determine any defects in the pipe. In manufacturing

9    facilities, the magnetostrictive transmitters or receivers may be stationary with the pipes moving

10   therebetween and simultaneously being inspected for any defects.

11         While one of the advantages of the present invention is the ability to carry out broad

12   inspections of large volumes of a plate type structure from a single positioning of the sensor, it is

13   anticipated that the complete investigation of a containment vessel or the like would require

14   multiple placements of the sensor in a variety of positions and orientations. For example, a

15   containment vessel might require the placement of the sensor in a sequential plurality of

16   positions along a predetermined scan line (which could be either horizontal or vertical to the

17   floor) that best achieves the inspection of the entire structure. In this manner, a progressive

18   inspection of an entire containment vessel is carried out without the requirement that all surfaces

19   of the vessel be accessed.

20         FIG. 11 is a pictorial view of a pipe 300 being inspected using a magnetostrictive

21   transmitter 314 and a magnetostrictive receiver 320 on the pipe 300 for transmission and receipt

22   of torsional waves. A current source 322 is applied to the pipe 300 at contact points 324 and 326

1    that connect around the entire pipe 300. The current source 322 can be either a DC source or a

2    low frequency AC (approximately 10Hz).

3         At a given frequency, more than one longitudinal (L) wave mode can exist in a pipe or

4    tube. The defect detectability of the MsS technology has been found to be hampered by the

5    presence of extraneous wave modes that were produced by the MsS itself and/or by mode

6    conversion of the transmitted wave at geometric features in pipelines, such as welds, elbows and

7    tees. In addition, when the pipe 300 under inspection is filled with a liquid, the liquid interacts

8    with the L-wave mode and causes many extraneous signals to be produced, which can

9    significantly degrade defect detectability.

10        In order to overcome these deficiencies in detecting defects in pipes or tubes containing a

11   liquid, a torsional wave is used for the inspection. The torsional wave is a shear wave that

12   propagates along the length of the pipe 300 or tube. Because the torsional wave is a shear wave

13   in a pipe or tube, its interaction with a liquid is negligible (unless the liquid is viscous).

14   Therefore, the defect detectability of torsional waves will not be hampered by the presence of

15   liquid in the pipe 300. In addition, the torsional wave exists as a single mode up to a

16   considerable frequency and, consequently, has minimal problems in defect detectability due to

17   the presence of extraneous wave modes. The torsional wave therefore is expected to have

18   significantly better defect detectability than the longitudinal wave modes.

19        To explain why a torsional wave would not be hampered by the presence of liquid in pipe

20   300, an explanation of the dimensional changes in the material due to magnetization and the

21   waves generated therefrom is provided in conjunction with Fig. 13. Referring to Fig. 13, the

22   larger arrows 350 shown in Figs. 13a, b and c represent the direction of propagation of the wave

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1    front. Referring to Fig. 13a, the dotted lines 352 give an exaggerated representation of the

2    dimensional changes in the ferromagnetic plate 354 when a shear wave is projecting in direction

3    350. Arrows 356 represent the oscillations occurring by the dimensional changes illustrated by

4    waves 352. For the purposes of illustration, the dimensional changes due to magnetization

5    caused by waves 352 and illustrated by arrows 356 have been exaggerated.

6        Referring to Figs. 13b and 13c, Lamb waves are projecting along the ferrogmagnetic plate

7    354. In Fig. 13b, the dimensional changes due to a symmetrical Lamb wave propagating in

8    direction 350 is illustrated in an exaggerated form. The smaller arrows shown in Fig. 13b

9    represent the dimensional changes of the plate 354. Fig. 13c shows an asymmetrical Lamb wave

10    that would propagate along plate 354, again with the small arrows representing dimensional

11    changes of the plate 354. As can be seen in Fig. 13, the dimensional changes in the Lamb waves

12    shown in Figs. 13b and 13c will react against any liquid contained in a pipe or container.

13    However, the use of a shear wave or a torsional wave as shown in Fig. 13a, because the

14    dimensional change is in the same plane of the plate 354, there would be no reaction or

15    interference by the liquid contained in any pipe or container. Therefore, the shear or torsional

16    wave is the ideal waveform to use if the plate or pipe is being checked that may contain a fluid.

17        As illustrated in Fig. 11, coil windings 342 and 346, transmitter 314 and receiver 320

18    that are used in the existing MsS L-wave inspection are installed around pipe 300. A high

19    ampere electric current is applied to pipe 300 by current source 322 applied at contact points 324

20    and 326 along the length of pipe 300. The electric current flowing along pipe 300 sets up a DC

21    bias magnetization in the circumferential direction of the pipe 300 necessary for MsS generation

22    and detection of torsional waves in the wall of pipe 300. The generated torsional waves

1 propagate along the length of pipe 300, and signals reflected from defects in pipe 300 are

2 detected in the same manner used for L-wave pipe inspection. The results of experimentation on

3 this aspect of the invention are contained in Fig. 12.

4 Figs. 12a - c are plots of signals received through the system of the present invention

5 utilizing torsional waves when used to test pipe 300 filled with water shown in Fig. 11. The data

6 were obtained using a 32 kHz torsional wave mode in a 4.5 inch outside diameter steel pipe

7 having a 0.337 inch thick wall and 168 foot length. The sample contained several simulated

8 defects. The DC current applied was approximately 150 amps, and the frequency of the MsS was

9 32 kHz. Signals from small simulated defects (whose cross sections were about one percent of

10 the total pipe 300 wall cross section) were not recognizable in these data. It is however expected

11 that the application of a higher DC current would permit detection of the small defects. The data

12 showed no effects of water.

13 Referring to the waveform shown in Figs. 12b and 12c, numerals 1 through 12 represent

14 the defects that occur in the pipe. The MsS transmitter 314 and receiver 320 along with coil

15 windings 342 and 346 are located at 54 feet down the pipe 300 from one end represented by end

16 F1. The other end of the pipe is represented by end F2. There are three welds in the pipe

17 represented by W1, W2 and W3, respectively, at 42 feet, 84 feet, and 126 feet. When the

18 torsional wave is propagated down the pipe towards end F2, there will be some small amount of

19 reflection of the signal from end F1 because of imperfect direction control as can be seen in Fig.

20 12b. Likewise, when the waveform is propagated towards end F1, there is some reflection of the

21 signal from end F2 as shown in Fig. 12c. Therefore, in Fig. 12b, the torsional wave signal is first

22 directed towards end F2. In Fig. 12c, the signal is directed towards end F1. Also, as can be seen

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1     in the signals, some of the simulated defects are so small they can hardly be distinguished. Other

2     simulated defects that are larger in cross-sectional area can be seen in the reflected signals shown

3     in Figs. 12b and 12c.

4         Referring now to Fig. 14, an alternative way of creating the circumferential magnetic field

5     in a pipe 400 is illustrated. Wrapped around the pipe 400 is a ferromagnetic strip 402 that

6     contains residual magnetization. The ferromagnetic strip 402 would typically be about an inch

7     wide and wrapped almost around pipe 400, with the exception of a small gap 404 at one end

8     thereof. The ferromagnetic strip 402 may be made from any material that has good

9     magnetization characteristics, such as nickel, grain-oriented silicon steel, or a magnetostrictive

10     material, such as TERFENDOL-D®. The objective is to have a flexible strip of material that has

11     good magnetization characteristics (ability to retain residual magnetization and high

12     magnetostrictive coefficient) for wrapping around pipe 400. The residual magnetization in the

13     ferromagnetic strip 402 is induced prior to wrapping around the pipe 400 by applying an external

14     magnetic field to the ferromagnetic strip 402 and then removing the external field (not shown).

15     After wrapping the ferromagnetic strip 402 around pipe 400, a magnetostrictive coil 406 is

16     placed around the magnetized ferromagnetic strip 402. The coil 406 may be of the common

17     ribbon type with a coil adapter 408 connecting the two ends of the ribbon type coil 406.

18         To press the magnetized ferromagnetic strip 402 against pipe 400, some type of external

19     pressure is necessary. The embodiment shown in Fig. 14 is a flexible strap 410 wrapping around

20     both ferromagnetic strip 402 and coil 406. The flexible strap 410 is pulled tight by means of

21     buckle 412, which in turn presses the ferromagnetic strip 402 against the pipe 400. The guided

22     waves are then generated in the ferromagnetic strip 402 and coupled into the pipe 400. For

1  detection, the guided waves in the pipe 400 are coupled to the ferromagnetic strip 402, which

2  guided waves are subsequently detected by the MsS coil 406 placed over the ferromagnetic strip

3  402.

4      For torsional wave generation and detection, the residual magnetization is induced along

5  the lengthwise direction of the ferromagnetic strip 402. For longitudinal wave generation and

6  detection, the residual magnetization is induced along the width of the ferrogmagnetic strip 402.

7  The pressing on the ferromagnetic strip 402 provides a mechanical coupling of the guided waves

8  between the pipe 400 and the ferromagnetic strip 402. The illustration as shown in Fig. 14 can

9  be either a transmitter or a receiver of guided waves (either longitudinal or torsional wave

10  modes) that are propagated along the pipe 400. Further studies have shown the ferromagnetic

11  strip 402 can be improved by the use of an iron/cobalt alloy (See FIG. 18).

12      Referring now to Fig. 15, another alternative is shown as to how to create a guided wave

13  in pipe 500. Just as in Fig. 14, in Fig. 15, a magnetized ferromagnetic strip 502 is wrapped

14  around the pipe 500. This ferromagnetic strip 502 can again be improved with the use of an

15  iron/cobalt alloy (See FIG. 18). Again, a gap 504 will exist between two ends of the

16  ferromagnetic strip 502. Also, the same as is the case in Fig. 14, a coil 506 is wrapped around

17  the ferromagnetic strip 502, which coil 506 is of the ribbon type and connected by a coil adaptor

18  508. However, the means of applying pressure against the ferromagnetic strip 502 to press it

19  against the pipe 500 is different in Fig. 15 from Fig. 14. In Fig. 15, a metal case or container 510

20  encircles the ferromagnetic strip 502 and coil 506. The metal case or container 510 is held

21  together by clamp 512. Inside of the metal case or container 510 is located a pneumatic or

22  hydraulic tube 514 that may be inflated. By inflating the tube 514, it presses the coil 506 and

1    ferromagnetic strip 502 against the pipe 500. Again, the embodiment as just explained in

2    conjunction with Fig. 15 may be used as either a transmitter or receiver of guided waves being

3    propagated along pipe 500.

4    The width of the magnetized ferromagnetic strips 402 or 502 is adjusted depending on the

5    frequency and the mode of the guided waves. For high frequencies, the magnetized

6    ferromagnetic strips 402 or 502 should be narrower; for lower frequencies, the magnetized

7    ferromagnetic strips 402 or 502 should be wider.

8    The feasibility of the approach explained in Figs. 14 or 15 has been proven in the

9    laboratory as illustrated in conjunction with Fig. 16. Using a 4-inch outside diameter pipe with a

10   .224 inch wall thickness pipe which was 9.3 feet long, a crude test was performed. The

11   magnetized ferromagnetic strip 402 or 502 was made of .01 inch thick nickel foil. The

12   magnetized ferromagnetic strips 402 or 502 were placed circumferentially around each end of the

13   pipe sample. The magnetized ferromagnetic strips 402 or 502 were mechanically coupled to the

14   outside surface of the pipe and in this case strapped using the method as shown in Fig. 14. Fig.

15   16 shows the data acquired at 64 kHz by transmitting the torsional wave from one end of the pipe

16   and detecting the signals at the other end of the pipe. The data clearly indicates Fig. 14 as being

17   an acceptable method for generating and detecting guided waves in pipes.

18   Referring to Fig. 17, a probe for generating and detecting guided waves in a tube 600

19   from inside the tube 600, which uses the same principle as the present invention, is illustrated. A

20   pneumatic tire 602 has ferromagnetic strips 604 and 606 bonded therearound. In Fig. 17,

21   ferromagnetic strips 604 and 606 represent a transmitter and a receiver, respectively, of the

22   torsional waves. The pneumatic tire 602 has a pressure valve 608 for inflating/deflating.

1    Inside of the pneumatic tire 602 are two bobbin type cores 610 and 612 about which a

2    transmitting coil 614 and receiving coil 616 are wound, respectively. To hold everything

3    together in their respective locations, the cores 610 and 612 are mounted on rod 618.

4    By inflating the pneumatic tire 602 through pressure valve 608, the magnetized

5    ferromagnetic strips 604 and 606 are pressed against the inside of tube 600. Thereafter, the

6    guided wave generated by transmitting coil 614 in the ferromagnetic strip 604 is coupled to the

7    tube 600 and propagates along the tube 600. Reflected signals from defects in tube 600 are

8    received back through the ferromagnetic strip 606 and detected by receiving coil 616. The type

9    of signal that will be generated will be a guided wave that propagates along tube 600. It is

10   envisioned that the configuration as shown in Fig. 17 will be inserted in the end of a tube 600 to

11   propagate a signal down the entire length of the tube to detect flaws or defects that may exist in

12   the tube 600. The cores 610 and 612 are ferrite or ferromagnetic steel to aid in the transmission

13   and receiving of magnetostrictive signals to and from the tube 600.

14   FIG. 18 is a plot of the MsS signals obtained with HYPERCO-50HS and Nickel at an

15   MsS operating frequency of 128 kHz. In prior experiments using ferromagnetic strips 402 and

16   502 for MsS operation (See Figs. 14 and 15), the ferromagnetic strip material was nickel, grain-

17   oriented silicon steel, or TERFENOL-D. Nickel has been primarily used up to this point since

18   good results have been obtained using nickel. Poor results have been obtained with the

19   remaining materials.

20   TERFENOL-D is a giant magnetostrictive material whose magnetostrictive coefficient is

21   higher than $1000 \times 10^{-6}$ compared to about $30 \times 10^{-6}$ in nickel, but is not available in strip form.

22   In addition, TERFENOL-D requires active application of a DC bias magnetic field to operate

1  MsS. With residual magnetization, the MsS signal was too weak to be useful. TERFENOL-D

2  therefore was determined to be inferior to nickel for the MsS operation.

3  Grain-oriented silicon steel, used for transformer cores, has a higher mechanical strength

4  and a higher Curie temperature than nickel. The MsS signal produced was found to be

5  comparable to that obtained with nickel. However, because silicon steel materials rust easily

6  these materials are difficult to use in practice.

7  In striving to further improve this MsS technology, Applicants searched for better strip

8  materials than nickel. The desired criteria for the material to make it better than nickel included

9  the following: (1) higher magnetostrictive coefficient, (2) operable with residual magnetization

10  and able to withstand the applied AC magnetic fields produced by MsS, (3) higher mechanical

11  strength, (4) higher Curie temperature (above which the material loses the magnetostrictive

12  properties), and (5) available in strip form.

13  Iron-cobalt alloys were investigated as potential strip materials for the present invention.

14  Iron-cobalt alloys have long been known to have higher magnetostrictive coefficients than nickel.

15  For example, alloys made of 49% Co, 49% Fe, and 2% V known as Permendur 49® have about

16  $60 \times 10^{-6}$ magnetostrictive coefficient. In addition, these alloys are mechanically stronger than

17  nickel (yield strength 40 to 60 kpsi versus less than 20 kpsi for nickel). These alloys have a

18  much higher Curie temperature than nickel (over 1700° F versus 662 ° F for nickel) and therefore

19  are suitable for high temperature applications. These alloys are also available in strip forms.

20  Applicants have investigated some of these iron-cobalt alloys for MsS use. These alloys

21  are commercially available and include Permendur-49®, HIPERCO-50®, and HIPERCO-50HS®.

22  The latter two are brand names for Carpenter Specialty Alloys, Carpenter Technology

1 Corporation. All of these alloys have similar chemical compositions, but are produced under

2 different heat treatment processes. Applicants have found that MsS performance obtained with

3 Permendur-49® and HIPERCO-50® was poorer than nickel.

4 However, the MsS performance obtained with HIPERCO-50HS® was found exceptional

5 and much better than nickel. A nomimal analysis provided by Carpenter Specialty Alloys shows

6 this material to consist of 0.01% C, 0.05% Mn, 0.05% Si, 48.75% Co, 1.90% V, 0.30% Nb,

7 with the balance Fe. The plot at FIG. 18 shows the MsS signals obtained with HYPERCO-50HS

8 and nickel at an MsS operating frequency of 128 kHz. The top trace 701 was obtained with a

9 0.006 inch thick strip of HIPERCO-50HS®. The bottom trace 702 was obtained with a 0.010 inch

10 thick strip of nickel. Both strips were approximately 0.5 inch wide. The data with HIPERCO-

11 50HS® in the top trace 701 were obtained at approximately a factor 3 lower amplification than

12 nickel. By comparing the signal amplitude and factoring in the amplification difference, the MsS

13 signal amplitude obtained with HIPERCO-50HS® was approximately 4.5 times greater than that

14 obtained with nickel.

15 Additionally, HIPERCO-50HS® withstood the applied AC magnetic fields produced by

16 MsS better than nickel. Therefore, a higher voltage excitation (by more than a factor of 2 than

17 for nickel) could also be applied to MsS to further increase the MsS signal amplitude. At 128

18 kHz improvements to MsS performance can be made by more than a factor of 10 than was

19 achievable with nickel. The actual performance enhancement obtainable with HIPERCO-50HS®

20 is expected to somewhat vary with the MsS operation frequency.

21 Although a description of a preferred embodiment of the apparatus and method of the

22 present invention has been described, it is anticipated that variations in the manner in which the

| | |
|---|---|
| 1 | basic sensor structure of the present invention may be utilized are possible. No specific |
| 2 | dimensions for the sensor structure described have been identified as such would be dependent |
| 3 | upon the specific plate type structures to be investigated. It is anticipated that sensors of a variety |
| 4 | of lengths could be utilized depending upon the requirements of the environment of |
| 5 | investigation. It is anticipated that other applications of the basic sensor structure described |
| 6 | herein will be discerned by those skilled in the art of nondestructive evaluation of materials. |
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